ARMY RESEARCH LABORATORY

Cost-Effective Manufacturing of Damage-Tolerant Integral Armor

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Abstract

The U.S. Army Research Laboratory (ARL) and the University of Delaware (UD) have developed an enabling technology to produce a polymer matrix composite-based integral armor with improved multihit ballistic capability. Current applications for integral armor composites include the Composite Armored Vehicle (CAV) technology demonstrator and Crusader self-propelled howitzer platforms. Present integral armor manufacturing processes involve adhesive bonding of a composite structure with ballistic armor tiles, spall shield, and nuisance cover. ARL, UD, and the CAV/Crusader composite structure contractor, United Defense Limited Partnership (UDLP), assessed through-thickness stitching to improve the multihit capability and reduce manufacturing costs. The patent-pending co-injection resin-transfer molding (CIRTM) process was used to produce a stitched, co-injected integral armor panel that demonstrated improved multihit capability. The spall shield was fabricated with a phenolic resin for fire, smoke, and toxicity protection, while the remainder of the integral armor (structural composite resin encapsulating the tiles and the nuisance cover) was fabricated with an epoxy resin for structural performance. Through-thickness stitching and CIRTM were used to enhance the damage tolerance and to reduce the cost of the armor.

Acknowledgments

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1. Background

Composite materials are playing a key role in the development of lightweight integral armor for military vehicles. Current and developing Army applications have identified the need for lightweight structural materials in order to enhance deployability and mobility of land combat forces. Several research and development programs have demonstrated the effectiveness of composite materials for combat ground vehicles to meet these needs. Recent advances include the development of composite/ceramic integral armor systems that provide significant improvement over monocoque composite structures with appliqué armor. To optimize the weight and performance of the vehicle, integral armor was developed as part of the Composite Armored Vehicle (CAV) Program with United Defense Limited Partnership (UDLP) [1]. The integral armor system exploits the structural contribution of the armor tiles to the structural design of the vehicle and allows the composite structure to perform a role in the ballistic protection of the vehicle to minimize areal density.

The integral armor designed by UDLP for the CAV upper hull and ramp structures is based on hybrid composite technology (i.e., combinations of polymeric, metallic, and ceramic materials) to meet multifunctional requirements such as structural; ballistic; signature management; electromagnetic interference (EMI) shielding; and fire, smoke, and toxicity (FST) protection. Such hybrid systems are designed for optimal utilization of not only the unique characteristics of each component material but also the synergistic effects of the entire system [2].

The manufacture of composite armor components generally involves multiple manufacturing steps to produce each composite layer. The individual layers are then adhesively bonded together in separate operations, resulting in an integral armor structure. These labor-intensive operations increase costs, pollution, part-to-part variability, and part-to-part dimensional tolerances and introduce defects at interfaces. Opportunities to enhance multihit/damage tolerance are limited by a multistep fabrication process.

2. Demonstration of Processing Innovations

Co-injection resin-transfer molding (CIRTM) is a patent-pending process developed by the U.S. Army Research Laboratory (ARL) and the University of Delaware (UD) as a cost-effective, pollution-reducing, performance-enhancing alternative to multistep vacuum-assisted resin-transfer molding (VARTM) for multifunctional composite structures [3]. A distinct advantage of the CIRTM process is the ability to include all of the composite armor elements in a single-preform assembly, including various fiberglass fabrics, an elastomer layer, and ceramic alumina tile [4–6]. At dissimilar material interfaces, a separation layer must be used. For integral armor applications, separation layers consisting of polysulfone film and epoxy-film adhesives were used. These CIRTM-compatible resin barriers have been shown to produce diffusion-enhanced adhesion (DEA) bonds with outstanding properties [7–10]. A high-permeability distribution media is placed on either side of the preform to enable rapid resin flow in lateral directions prior to through-thickness preform infiltration. Since no adhesives are used in secondary bonding operations and the entire process is performed within a closed, controlled system, volatile organic compound (VOC) hazardous air pollutant (HAP) emissions are drastically reduced.

The CIRTM process introduces four distinct advantages for fabricating multiresin composite parts. First, Newton et al. [11] reported significant pollution-prevention benefits to the application of CIRTM in production of composites. Second, CIRTM reduces costs by allowing single-step manufacture of parts by reducing cycle time and secondary operations. Third, the co-injection process results in a tougher interface between layers when compared with manufacturing the layers separately and then postbonding them together. Reduction of manufacturing steps is shown in Figure 1. Finally, and perhaps most important for realizing the potential of integral armor, the co-injection process enables through-thickness reinforcement of multiresin systems, which provides optimal load transfer between structural, fire-protective, and shock-wave-management layers of the composite armor.

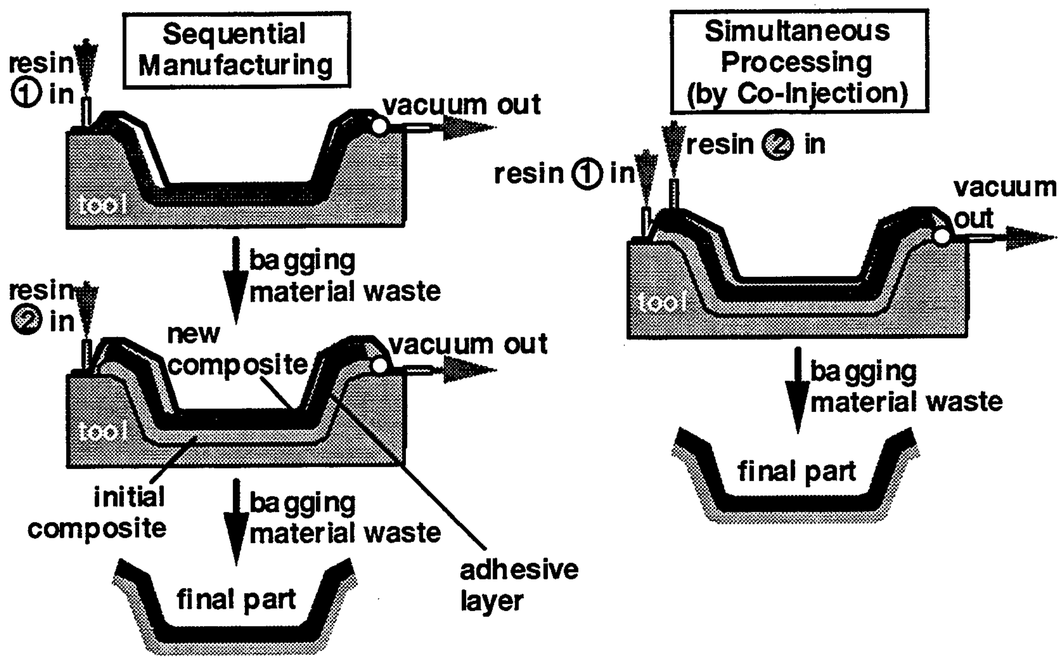

Figure 1. **Schematic Comparing Traditional Sequential Manufacturing to the CIRTM Process.**

To demonstrate the feasibility of the co-injection process to enable through-thickness reinforcement and improved ballistic performance in a manufacturing environment, several 2-ft × 2-ft targets were fabricated for ballistic evaluation. The baseline targets were fabricated by UDLP, using a conventional multistep manufacturing process where the nuisance cover, tiles, and fiberglass composite structure were placed in a dry mold and VARTM was used to wet the part out with an epoxy resin (Applied Poleramic SC-15). After wet-out and cure, the part was demolded and the ballistic liner was placed on the previously cured laminate and a second VARTM manufacturing operation was used to wet-out the ballistic liner with a phenolic resin (Applied Poleramic SPH-4). Adhesion between the two resins (epoxy and phenolic) was minimal, resulting in poor multihit performance. After a single shot, there was extensive damage between the epoxy composite interface with the phenolic composite ballistic liner. The second shot resulted in complete separation of the ballistic liner from the epoxy composite (Figure 2).

To improve multihit performance, through-thickness stitching was employed to join the composite backing plate with the ballistic liner. The CIRTM manufacturing process was used to

Figure 2. Ballistically Tested Panel Manufactured Using Traditional Multistep Process. Photo Courtesy of UDLP.

fabricate the part in a single step, while maintaining separate and discrete layers with the two resin systems. A schematic of the co-injected, stitched integral armor target is shown in Figure 3.

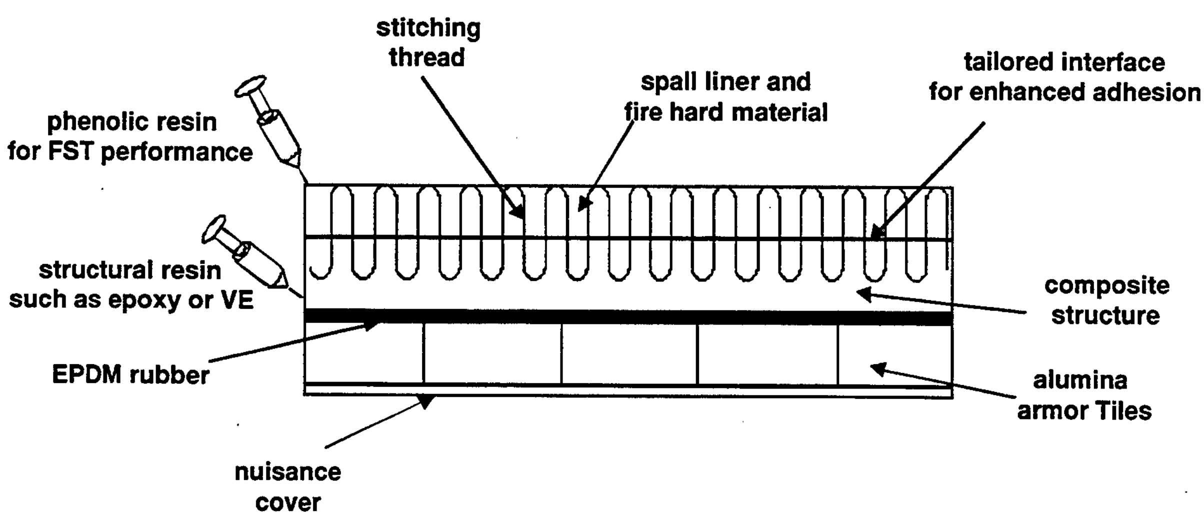

Figure 3. Schematic of Through-Thickness Stitching and Co-Injection of Integral Armor.

The co-injected, stitched integral armor target resulted is a composite with a stitched, co-cured interface between the separate resin layers that provides superior performance and reduced cost compared to traditional multistep fabrication approaches. For this target configuration, a UDLP-proprietary barrier was used as a means of controlling the flow of the two resins. Co-injecting the phenolic fire-protective layer with the epoxy structural layer in a single composite part improved the multihit performance of the targets.

Ballistic testing showed multihit performance of up to six shots into a single target without separation of the spall liner from the epoxy composite (Figure 4). The stitching and toughened interlayer bonding clearly improved the damage tolerance of the panels apparent through the significant reduction in lateral delamination. Previously reported results show that interlaminar shear strength provided by CIRTM is enhanced relative to the weakest resin in the specimen [5]. In all CIRTM-manufactured specimens, failure occurred within the phenolic composite layer. For the Mode I fracture toughness testing, failure of the co-injected samples was observed to be cohesive; conversely, the failure of the secondary-bonded multistep manufactured panels was adhesive failure between the epoxy adhesive and the phenolic composite. During Mode I crack propagation, multiple delamination planes formed in the phenolic laminate, which is a reflection of the higher toughness offered by the CIRTM interphase. Results of both interlaminar shear and Mode I fracture toughness for CIRTM were comparable to or exceeded the phenolic baseline. The multihit performance of the stitched co-injected integral armor targets showed substantial improvement when compared to targets fabricated with the sequential manufacturing process.

Another advantage of the co-injection process is a lower cost manufacturing process. Figure 5 compares the cost of the co-injection process with a sequential two-step manufacturing process for an integral armor structure. The activity-based cost analysis was performed on the ramp section of the CAV in a simulated manufacturing model. Manufacturing models incorporating co-injection and sequential injection processes have indicated that co-injection will result in approximately a 15% cost savings over the sequential injection process. These savings are mostly due to the decreased material handling time and decreased cycle time for production. Materials savings (e.g., bagging materials, waste resin, etc.) are also a component. Not included

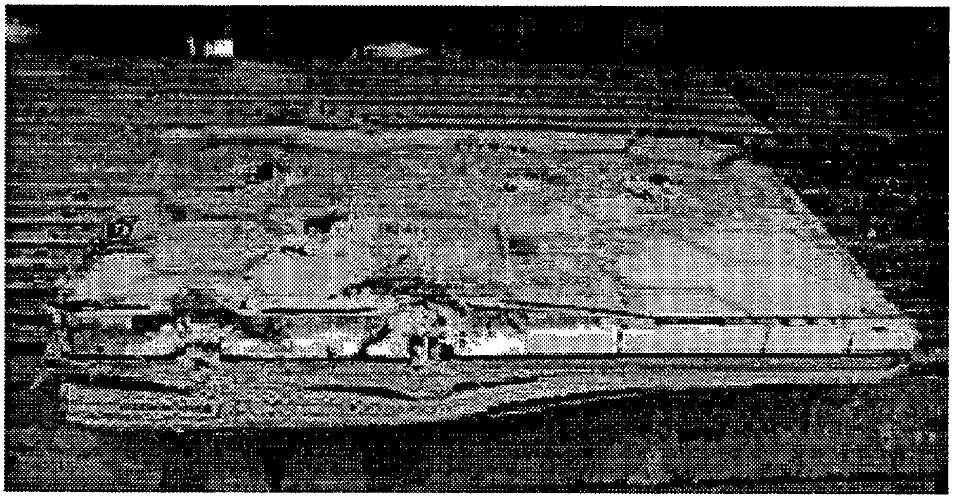

Figure 4. Co-Injected, Stitched Integral Armor Target Exhibiting Six-Shot Multihit Performance Without Separation of the Ballistic Liner Fabricated With Stitching and Co-Injection. Photo Courtesy of UDLP.

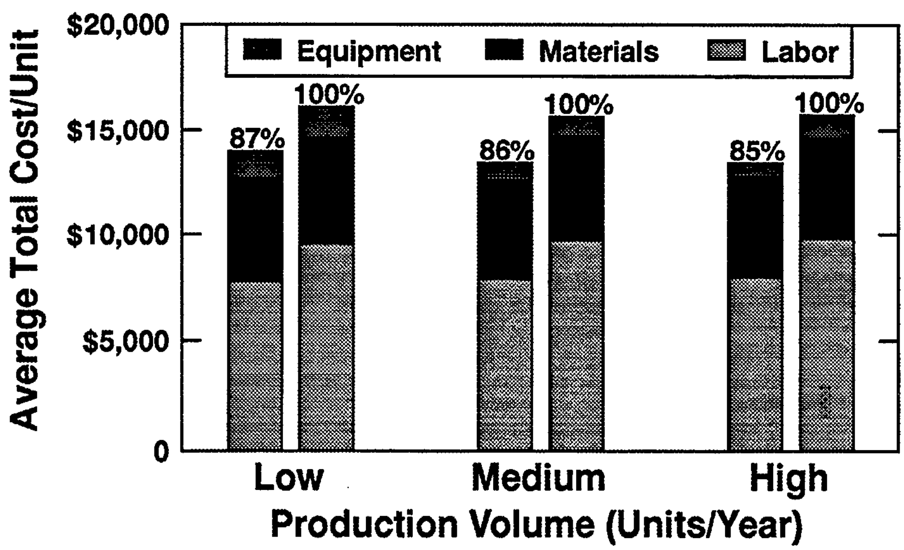

Figure 5. Activity-Based Cost Analysis Showing the Cost Savings of CIRTM.

in the model are environmental cost savings issues. More detail on environmental cost savings for this process are covered elsewhere [11]. Greater annual production volume may also be achieved from co-injection, given an equal capital investment in manufacturing equipment [12].

3. Composite Armor Testing

3.1 Test Matrix. Previous work studied the ballistic properties of polyester- [13] and epoxy-based [14, 15] composite panels. A goal of this study was to provide ballistic properties of more cost-effective and VARTM/CIRTM process-friendly vinyl-ester resin systems. To test the equivalency of a VARTM-compatible vinyl-ester resin system (Dow Derakane 411-C-50) with a VARTM-compatible toughened epoxy (Applied Poleramic SC-4) and a polyester prepreg baseline system (CYCOM 4102), a series of S2-glass composite panels was fabricated, with areal densities of 7 psf and 20 psf. A 24 oz/yd^2, 5 × 5 plain weave, S2-glass fabric was used in the 20-psf armor systems, while an 18 oz/yd^2, 2 × 2 twill weave S2-glass fabric was used in the 7-psf armor systems. The effect of through-thickness stitching was assessed for ballistic damage confinement for the VARTM-produced panels. Additionally, the 20-psf panels were tested with 0.7-in-thick AD90 alumina ballistic tiles bonded to the outer surface. Tables 1 and 2 summarize the test matrix for the 7- and 20-psf panels, respectively.

Table 1. Testing Matrix for Panels Without Alumina Tiles

Material	Stitching	Areal Density (psf)	V_{50} Against .50-cal. FSP (fps)	.50-cal. FSP Projectile Velocity for Testing (fps)
Polyester Prepreg	No	7.0	1,770	1,550
VARTM Vinyl Ester	No	7.2	1,780	1,550
VARTM Vinyl Ester	Yes	7.0	—	1,550
VARTM Epoxy Resin	No	7.0	1,750	1,550
VARTM Epoxy Resin	Yes	7.0	—	1,550

Note: FSP = fragment-simulating projectile.

The stitched composite targets were fabricated using the following procedure. First, the fabric was laid-up dry. The dry preform was stitched using a chain-stitching machine with a MIL-T-87128, 3-cord, soft, Kevlar thread (2,000 denier). The dry preform was stitched in both the X and Y directions, with stitch rows on 1-in centers. The stitch spacing within the stitch row was approximately five threads per inch. The stitch spacing along the stitch row varied slightly,

Table 2. Testing Matrix for Panels With Alumina Tiles

Material	Stitching	Areal Density (psf)	20-mm FSP Projectile Velocity for Testing (fps)
Polyester Prepreg	No	20	2,700
VARTM Vinyl Ester	No	20	2,700
VARTM Vinyl Ester	Yes	20	2,700
VARTM Epoxy Resin	No	20	2,700
VARTM Epoxy Resin	Yes	20	2,700

due to the weight of the preform and the inability to accurately index the preform by hand. An estimate of through-thickness reinforcement is 3–4% volume fraction. It should be noted that two threads pass completely through a single needle hole in a chain stitch pattern, effectively doubling the thread denier.

3.2 Ballistic Testing. Four-shot V_{50} testing was used to determine a velocity at which the projectile would likely penetrate the 7-psf targets using a .50-cal. fragment-simulating projectile (FSP). Targets were fabricated using the CYCOM prepreg material and using the SC-4 resin to perform the V_{50} testing. From the 4-shot V_{50} results, a reduced velocity was chosen to test the remainder of the targets. By performing a 4-shot V_{50}, comparing the results and reducing the velocity, it was confidently assumed that the energy level imparted to the targets would cause sufficient damage to the laminate without completely penetrating the target. This allowed for comparison of the ballistically impacted panels based on the extent of damage given relatively equivalent input energies. A velocity of 1,550 fps was chosen for the constant velocity testing of the remaining targets. This allowed for subsequent structural testing at a constant velocity and correlation with residual strength models. Testing was done in accordance with NIJ Standard 0101.03. Due to the light powder charge in the projectile case, velocity varied somewhat on the constant velocity testing with the .50-cal. projectile but still permitted an accurate relative level of comparison between the various targets. Velocity was determined using light screens and a chronograph.

The composite backing plates for the 20-psf alumina-composite armor targets were fabricated in a similar fashion as the 7-psf targets, and a single alumina hex tile was bonded to the face using an epoxy-paste adhesive. A 0.4-mm to 0.6-mm glass bead was used as a spacer to maintain a constant thickness within the bondline. This combination provides a line-of-sight (LOS) areal density of 20 psf to the projectile. For the ceramic-faced composite armor targets, a 20-mm fsp at 2,700 fps was selected for the projectile and velocity given an estimated lower-bound 3,000-fps V_{50}. The velocity was chosen to impart a significant level of damage to the projectile with little or no penetration of the projectile into the composite backing plate.

3.3 Extent of Damage. The damaged targets were nondestructively tested to determine the extent of delamination resulting from the projectile impact. All of the targets were ultrasonically scanned using four gates to record delamination profiles through the thickness of the panel. Gate 1 is located nearest the impact surface of the composite backing plate, Gate 4 near the back surface, and Gates 2 and 3 equally spaced through the thickness. A 5-MHz focused transducer was used to ultrasonically scan targets. After the panels were scanned, the images were imported into image processing software to determine a percentage of damage within the panel. Percent delamination was determined through edge enhancement of the image and highlighting the damage region. A calculation could then be done, which compared the highlighted damaged portion to the whole image, providing a percent delamination.

3.4 Results.

3.4.1 V_{50} Testing and Data Normalization. Tables 3 and 4 show the results of the V_{50} testing for the SC-4 and polyester 7-psf targets. It is understood that this limited number of shots does not provide an accurate V_{50} ballistic limit for these material systems. It does, however, provide a good indication of what reduced velocity across all the panels should be used for a "constant velocity" to assess the effects of material variations such as through-thickness stitching and resin system. Based on these 4-shot V_{50} results, a velocity of 1,550 fps was chosen as the impact velocity for the remainder of the 7-psf targets.

Table 3. SC-4 Panels, Nonstitched, .50-cal. FSP

Panel No.	Areal Density (psf)	Velocity (fps)	Comments
SC-4-3	7.0	1,749	Complete
SC-4-2	6.9	1,536	Incomplete
SC-4-4	6.9	1,685	Incomplete
SC-4-1	6.9	1,729	Incomplete
V_{50}: 1,740 fps			

Table 4. CYCOM Panels, Nonstitched, .50-cal. FSP

Panel No.	Areal Density (psf)	Velocity (fps)	Comments
CYCOM-1	7.0	1,729	Incomplete
CYCOM-2	7.0	1,776	Partial, Hit Witness
CYCOM-3	7.0	1,808	Complete
CYCOM-4	7.0	1,663	Incomplete
V_{50}: 1,770 fps			

While it is desirable to test at a common impact velocity, it is not possible to accurately obtain equivalent velocities using charged projectiles. Figure 6 shows the maximum extent of delamination data vs. penetrator velocity for the 20-mm vinyl-ester stitched and unstitched panels as an example of the method of normalization of extent of damage measurements against a common impact velocity. Here, the desired impact velocity was 2,700 fps and the average maximum delamination was 30% of the planar area of the target. Normally, one might normalize data above and below 2,700 fps back to 2,700 fps by following the heavy solid line back to zero. However, since the expected relationship between damage and velocity (below V_{50}) generally looks more like the curved dashed line, it is more reasonable to attempt to normalize damage data along an expected slope within the region of the neighboring data. Since the V_{50} for these targets was determined to be around 3,000 fps and a maximum circular delamination zone of 72% is assumed at V_{50}, a line was constructed from this point back through the data. This line was used for normalizing the damage zone data to a common velocity of 2,700 fps. A similar procedure was used for the 7-psf target data normalized to 1,550 fps.

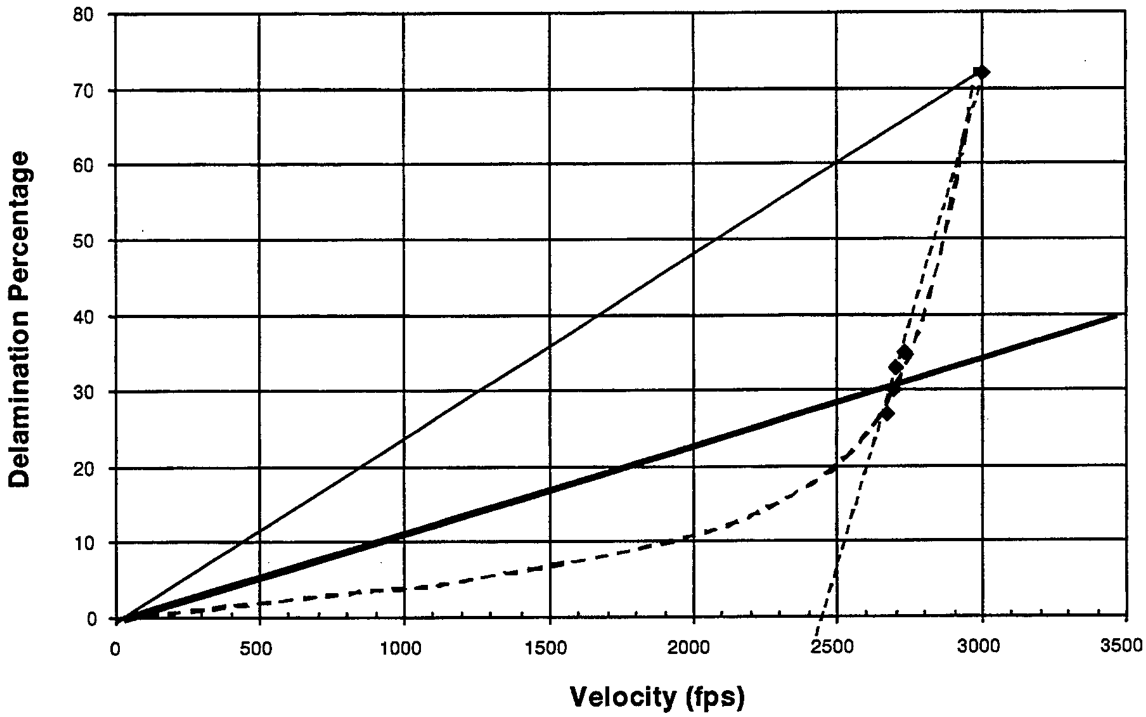

Figure 6. Plot of 20-mm Vinyl-Ester Panel Delamination Data Showing Normalization Procedure.

Figure 7 shows a cross section of one of the nonstitched 7-psf targets after ballistic impact. Figure 8 shows the ultrasonic scan images for the panel of Figure 7 for each of the four gates, with the first gate being near the top surface of the target.

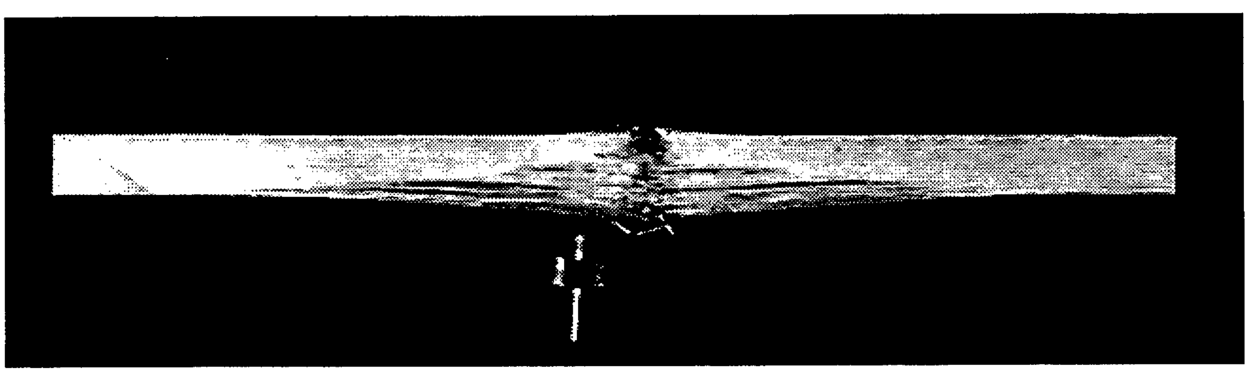

Figure 7. Cross Section of a 7-psf Target After Ballistic Impact.

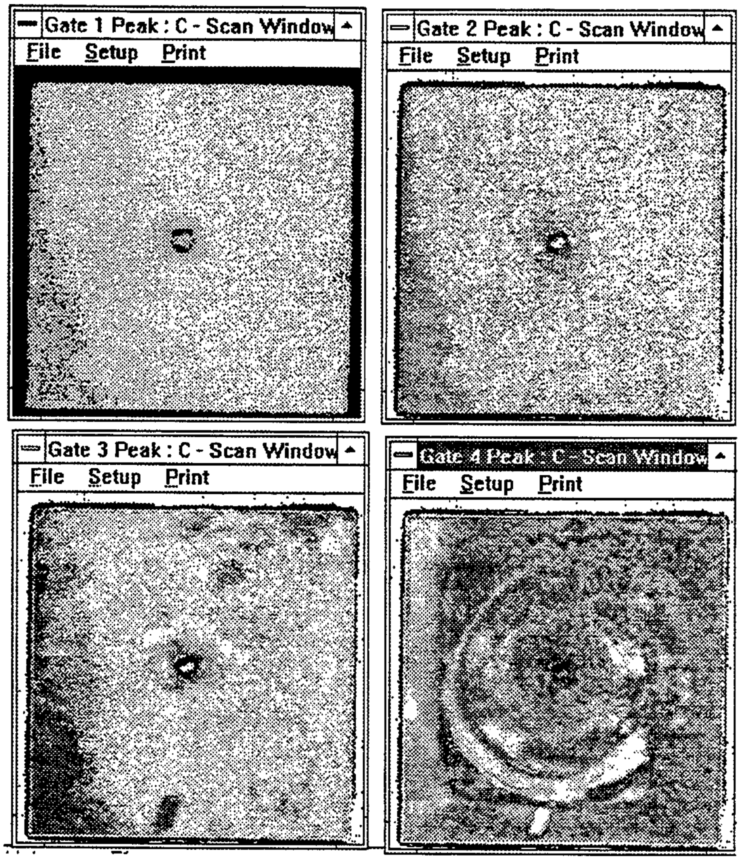

Figure 8. Ultrasonic Scan Plots for the 7-psf Panel Shown in Figure 7.

3.4.2 7-psf Target Data. Figure 9 shows the outer surface (impact side) of one of the 7-psf panels after ballistic impact. The extent of damage near the first gate is clearly visible. Table 5 provides the delamination data for all the 7-psf targets.

Figure 10 depicts the average delamination sizes at each gate for the data of Table 5, showing the conical shape of damage through the thickness of the laminates. The areas under the curves in Figure 10 are approximate estimates of the volume of damage and, since the delamination data is normalized to a common velocity, the volume of damage is a useful comparison of damage density between panels. The shape of the curves in Figure 10 is important to consider. A convex curve indicates an armor that delaminates primarily near the back surface and does not absorb energy uniformly through its thickness. A concave curve is indicative of an armor that more evenly distributes its damage through the thickness. A superior damage-tolerant armor is one that uniformly absorbs energy through the thickness and that offers the potential for high residual

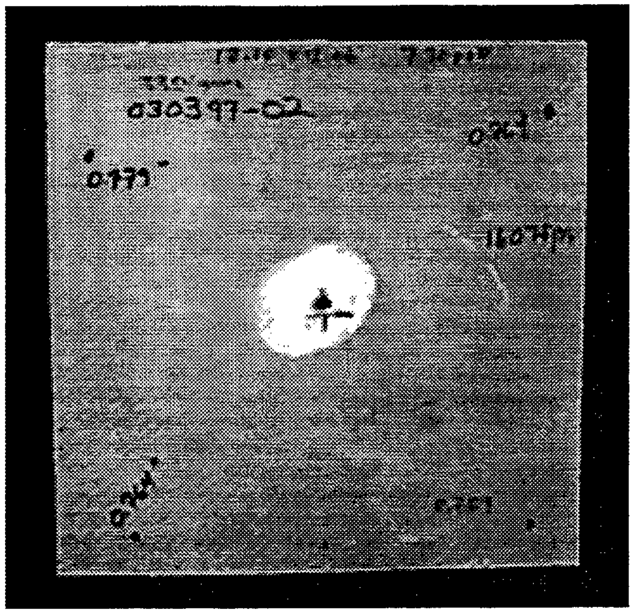

Figure 9. Front Surface of a 7-psf Panel After Ballistic Impact. Gate 1 Delamination Zone Is Visible.

Table 5. Delamination Data for the 7-psf Targets

Panel ID	Panel ID No.	Gate 1 (%)	Gate 2 (%)	Gate 3 (%)	Gate 4 (%)	Velocity (fps)
SC-4	2217-4	2.2	3.5	8.0	50.6	1,729
SC-4	2217-5	0.9	3.4	11.8	21.7	1,607
VE	2716-1	1.0	16.6	16.7	17.6	1,579
VE	2716-2	5.0	17.3	17.9	18.6	1,617
CYCOM	2716-5	9.1	12.4	19.6	19.8	1,608
CYCOM	2716-6	0.8	15.4	17.5	19.7	1,578
SC-4-s	2217-7	1.0	6.2	12.9	13.8	1,571
SC-4-s	2217-8	2.6	5.7	9.0	5.5	1,512
VE-s	2716-3	0.2	8.0	8.6	9.0	1,566
VE-s	2716-4	0.4	14.3	18.5	18.9	1,615

Notes: SC-4: unstitched 7-psf SC-4 epoxy VARTM composite.
VE: unstitched 7-psf vinyl-ester VARTM composite.
CYCOM: unstitched 7-psf polyester prepreg composite.
SC-4-s: stitched 7-psf SC-4 epoxy VARTM composite.
VE-s: stitched 7-psf vinyl-ester VARTM composite.
SC-4-t: unstitched 20-psf SC-4 epoxy VARTM composite with alumina tile.
VE-t: unstitched 20-psf vinyl-ester VARTM composite with alumina tile.
CYCOM-t: unstitched 20-psf polyester prepreg composite with alumina tile.
SC4-t-s: stitched 20-psf SC-4 epoxy VARTM composite with alumina tile.
VE-t-s: stitched 20-psf vinyl-ester VARTM composite with alumina tile.

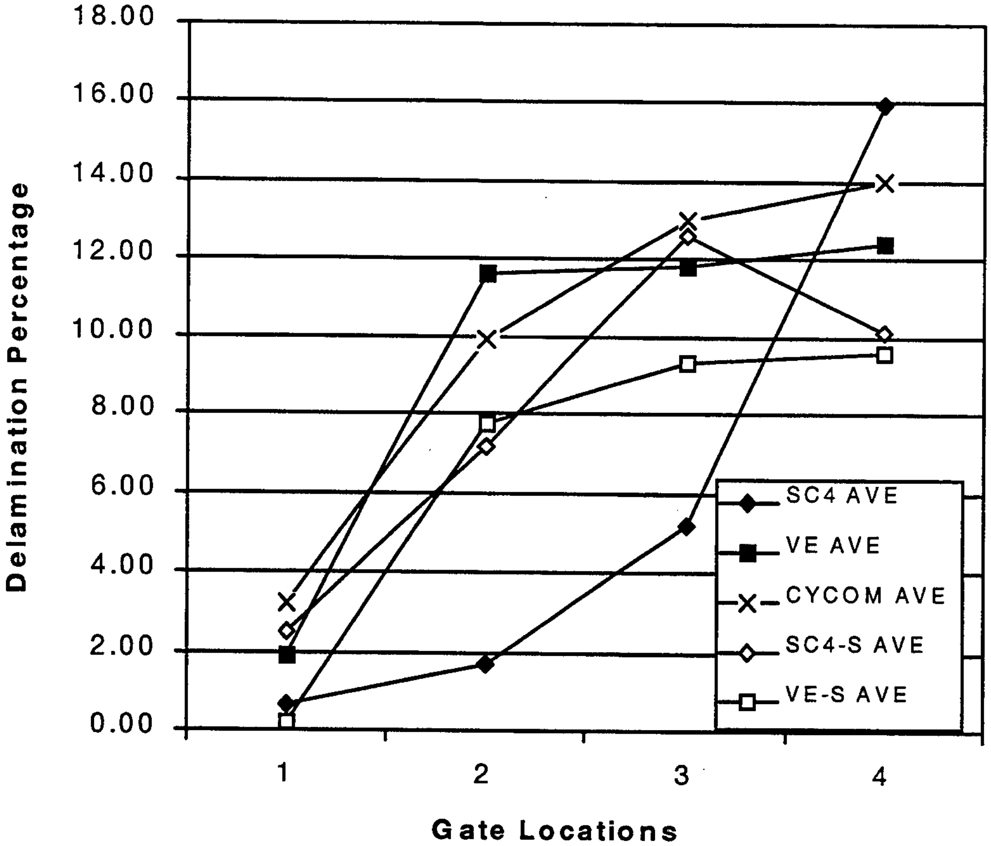

Figure 10. Averaged Gate Delamination Data for 7-psf Panels Normalized to 1,550 fps.

strength. Based on these materials, VE-S outperforms VE, SC-4, and CYCOM. The benefits of stitching are shown in the figure for vinyl-ester panels (lower extent of damage) but most dramatically in the case of SC-4 panels. Thus, while the SC-4 toughened epoxy does not appear to outperform the lower-toughness vinyl ester, stitching does appear to provide a greater damage tolerance and, in the case of SC-4, provides for a beneficial transition from a convex to a concave damage zone shape through the thickness.

Figure 11 compares damage volumes (calculated as the average of the four gates) and maximum delaminations. A lower maximum delamination is preferable for damage tolerance and multihit performance. It is also preferential to minimize the damage volume for the same reasons; however, for a given maximum delamination size, a higher damage volume may be indicative of more efficient energy dissipation in the panel.

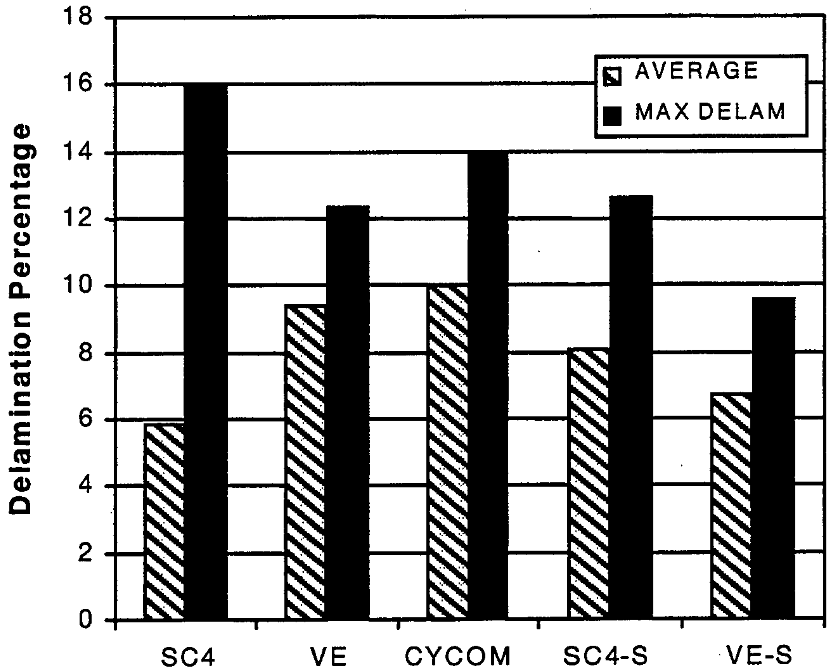

Figure 11. Average and Maximum Delamination Data for 7-psf Panels.

Another way of comparing panels is to compare the ratio of the average delamination to the maximum delamination. Figure 12 shows this ratio (hatched bars), and, for ease of comparison, the solid bars indicate the average-to-maximum ratios normalized to the SC-4 panel. A ratio of unity would be the ideal situation since it represents the case where damage is uniform through the thickness and the entire thickness has contributed to the dissipation of energy providing a more damage tolerant postballistic structure and, possibly, increasing the ballistic performance of the armor through more efficient dissipation of energy. However, since it is important to consider both the desire to minimize the maximum extent of delamination (Figures 10 and 11) and the desire to optimize the uniformity of damage through the thickness (Figure 12), the ratio of these two (AVE/MAX^2) is insightful for comparison of armors. AVE/MAX^2 is simply the ratio of the normalized average (AVE/MAX) to the maximum (MAX). Consider two panels in which one has a conical delamination pattern through the thickness and one has a uniform (cylindrical) delamination pattern through the thickness. If both have an average delamination diameter (AVE) of 2 in, then the conical pattern has a maximum delamination diameter (MAX) of 4 in and the cylindrical pattern has a maximum delamination of 2 in. The MAX value is

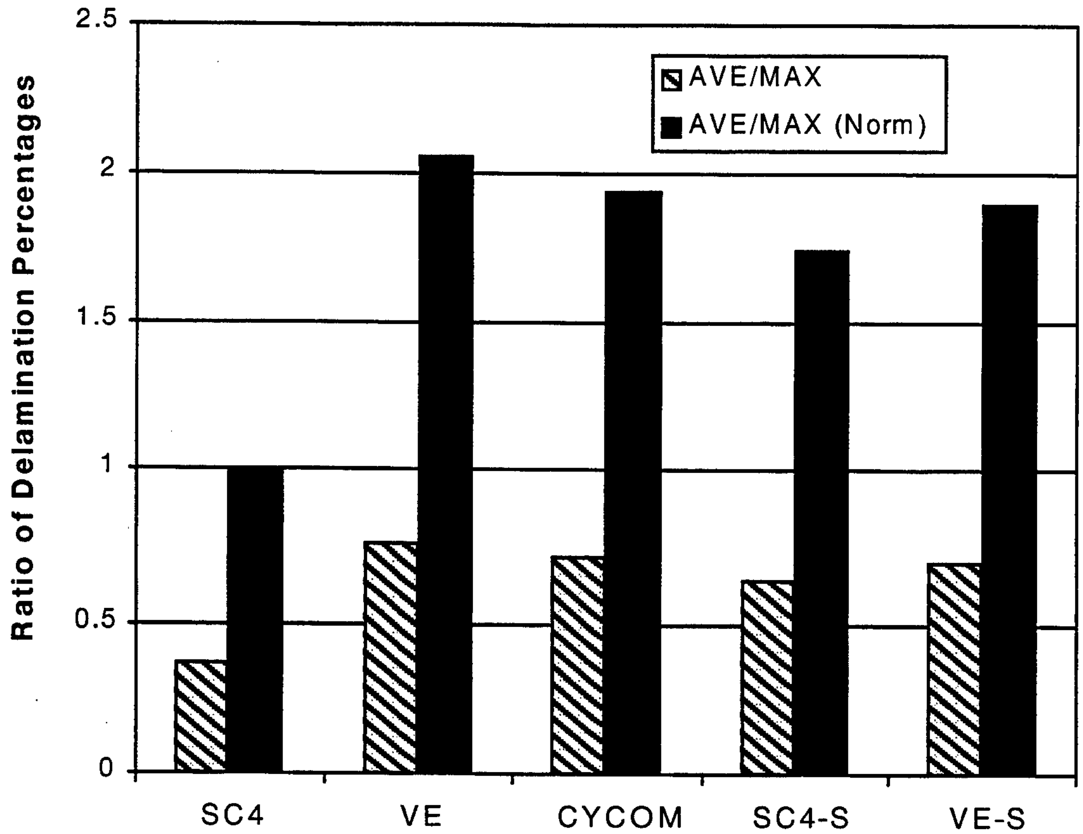

Figure 12. AVE/MAX Delamination Data for 7-psf Panels.

indicative of an armor's damage tolerance. The AVE value is indicative of the energy absorbtion. However, to distinguish between armors with different delamination patterns, the ratio of AVE/MAX can be used to indicate the relative uniformities of energy absorption between different armors. For example, the conical delamination pattern results in an AVE/MAX value of 0.5, while the cylindrical pattern obviously results in an AVE/MAX value of unity. Values closer to unity are desirable. Now, consider a third armor that results in a desirable cylindrical delamination pattern but with a 4-in maximum delamination. For this armor, the apparent energy absorption indicator (AVE) is 4 in. However, the AVE/MAX uniformity indicator is still unity. To quantitatively compare these two armors, it is useful to use a third performance indicator by taking the ratio of uniformity to the maximum value AVE/MAX^2. Maximizing this value maximizes the efficiency of the armor at absorbing energy while maintaining high structural and multihit damage tolerance. For the 4-in conical example, the "efficiency" parameter is 0.125. For the 4-in cylindrical delamination, the efficiency is 0.25,

and, for the 2-in cylindrical delamination, the efficiency is maximized at 0.5. In terms of these definitions, delamination patterns closer to cylindrical (e.g., concave vs. convex conical curvatures) are more efficient. Stitching tends to limit delamination in latter plies through the thickness and energy is absorbed through delamination of plies nearer the front of the armor backing plate, resulting in a transition from convex conical patterns to concave conical patterns. As shown in Figure 13, this comparison brings out the value of stitching for both the VE and SC-4 panels.

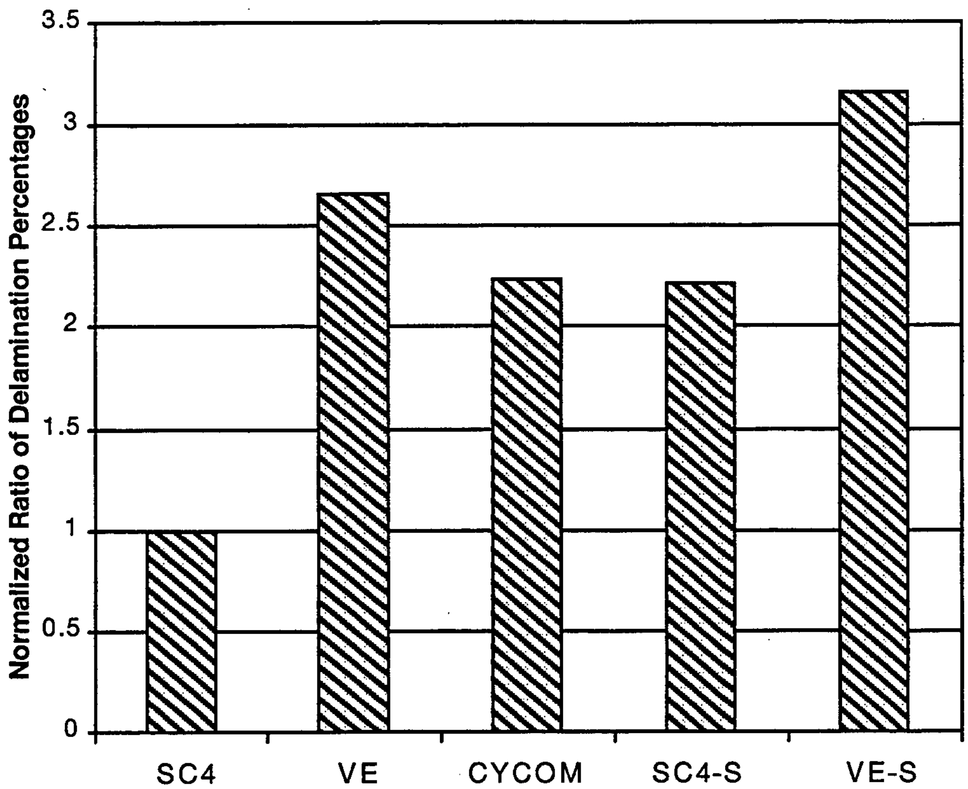

Figure 13. AVE/MAX^2 Delamination Data for 7-psf Panels.

3.4.3 20-psf Target Data. Figure 14 shows the front surface of a stitched vinyl-ester 20-psf panel prior to ballistic testing. The stitching pattern and the placement of the tile is apparent in the photograph. Table 6 shows the delamination data at each of the four gates for each 20-psf test panel.

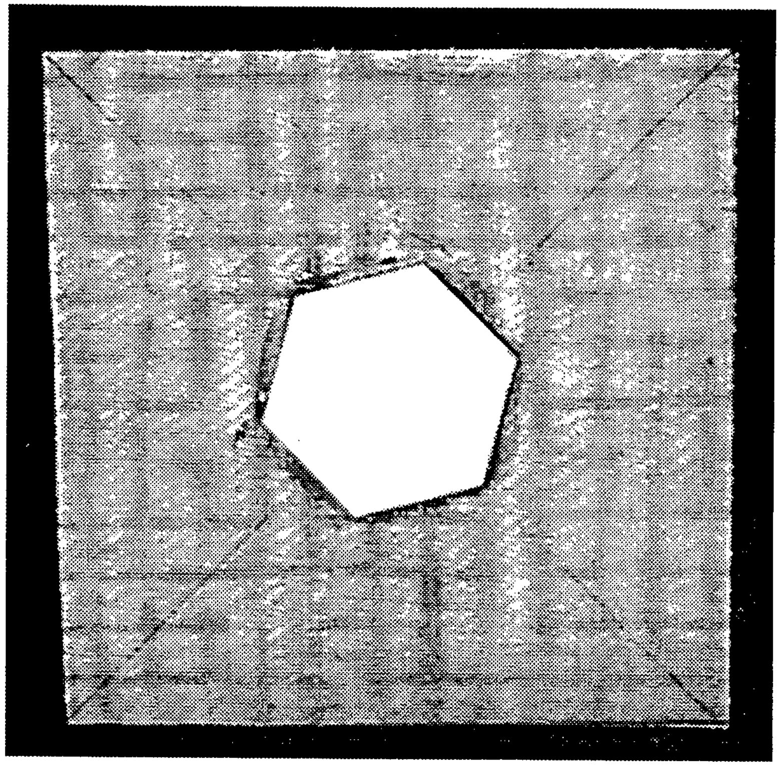

Figure 14. Front Surface of a Stitched Vinyl-Ester 20-psf Panel Prior to Ballistic Impact.

Table 6. Delamination Data for the 20-psf Ballistic Panels

Panel ID	Panel ID No.	Gate 1 (%)	Gate 2 (%)	Gate 3 (%)	Gate 4 (%)	Velocity (fps)
SC-4-t	2715-5	47	49	46	50	2,680
SC-4-t	2715-6	30	47	47	45	2,683
VE-t	2715-7	27	36	36	33	2,700
VE-t	2715-8	29	30	33	30	2,693
CYCOM-t	2715-3	33	36	52	48	2,684
CYCOM-t	2715-4	34	36	41	44	2,690
SC-4-t-s	2351-5	17	37	38	38	2,700
SC-4-t-s	2351-6	13	31	40	40	2,672
VE-t-s	2715-1	32	33	33	35	2,735
VE-t-s	2715-2	32	28	29	27	2,669

Figures 15–18 for the 20-psf panel delamination results follow the same logic presented in Figures 10 through 13 for the 7-psf panels. Note that, for the 20-psf panels, that are tested with a heavier projectile at a higher velocity (20 mm at 2,700 fps for the 20-psf panels

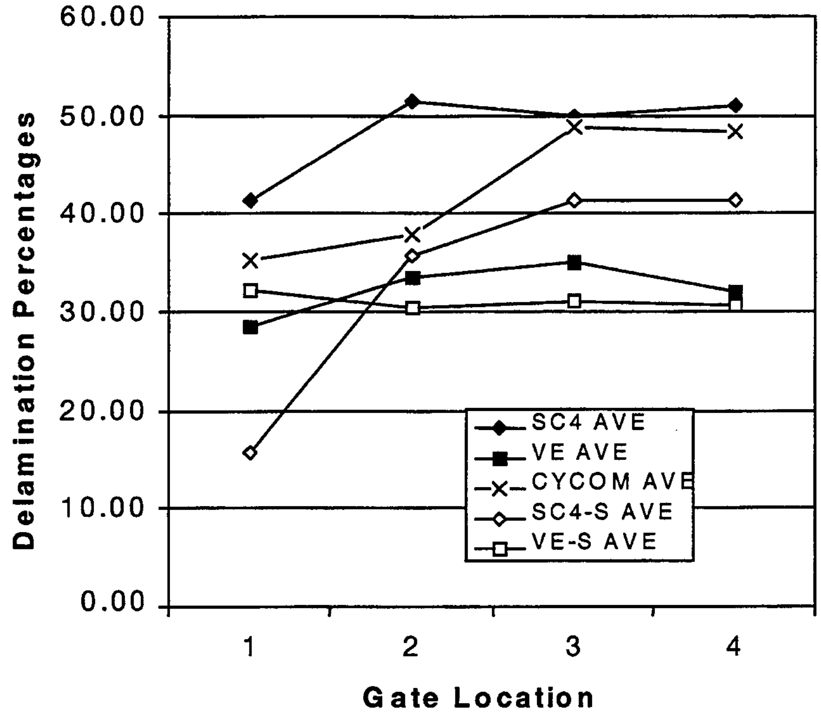

Figure 15. Averaged Gate Delamination Data for 20-psf Panels Normalized to 2,700 fps.

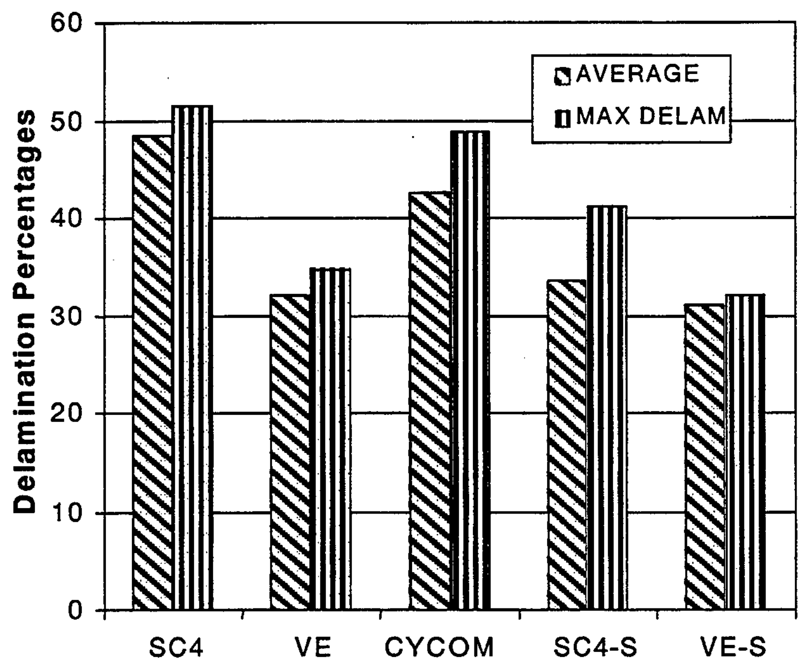

Figure 16. Average and Maximum Delamination Data for 20-psf Panels.

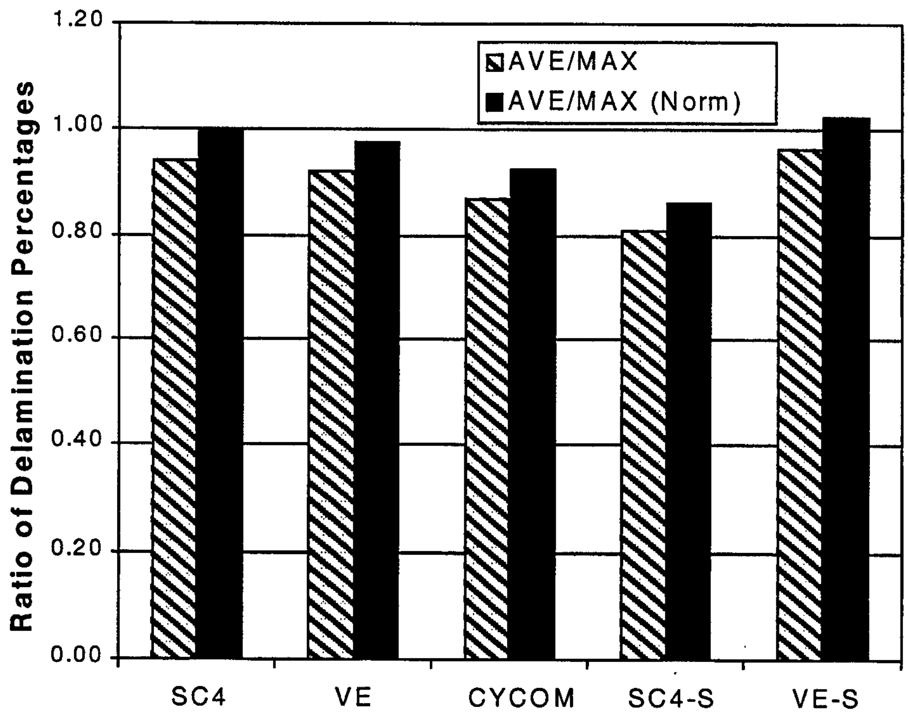

Figure 17. AVE/MAX Delamination Data for 20-psf Panels.

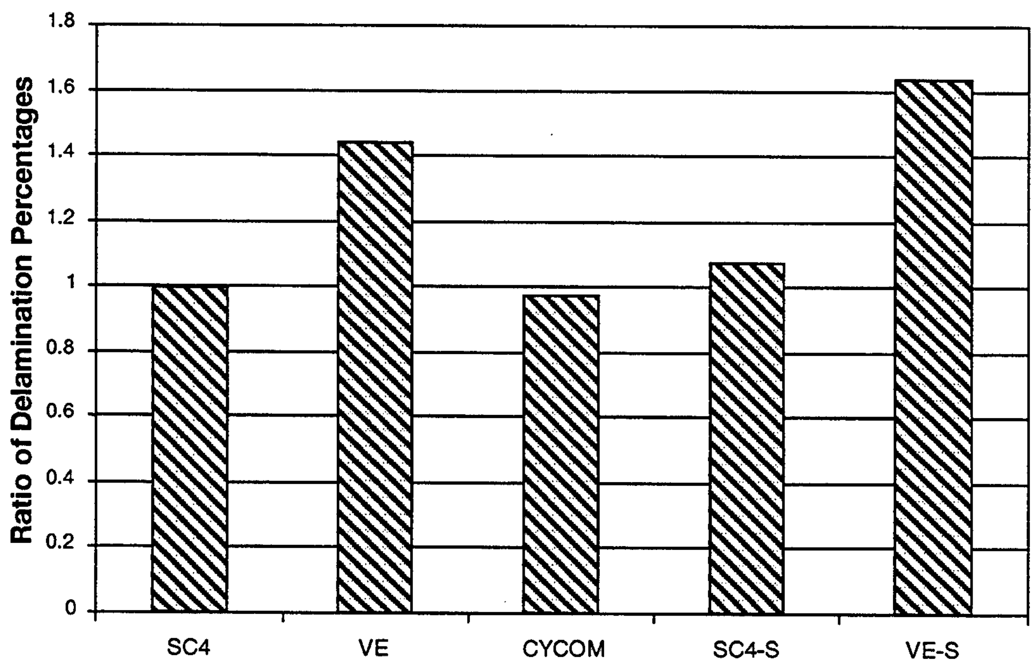

Figure 18. AVE/MAX^2 Delamination Data for 20-psf Panels.

vs. .50 cal. at 1,550 fps for the 7-psf panels), the ceramic tile absorbs most of the impact energy and changes the characteristics of damage through the thickness of the composite panel. Minimal penetration into the backing plate occurs during the tests, and delamination occurs due to stress-wave propagations during impact. As in the 7-psf targets, vinyl-ester appears to outperform both SC-4 epoxy and polyester prepreg panels in terms of armor efficiency, as defined previously. In the case of VE, the benefits of stitching will become significant at high velocities where penetration and arrest of the projectile will occur, leading to a higher V_{50} per areal density. For SC-4, stitching provides a more damage-tolerant armor resulting in a smaller damaged region.

4. Conclusions

VARTM techniques were demonstrated to be viable low-cost methods for producing structural laminates with integrated armor for ground combat vehicles by UDLP. Damage tolerance and multihit performance of the integral armor system over conventionally fabricated targets were significantly improved by stitching. CIRTM was the enabling technology that provided the capability to manufacture a single composite article in a single step, with discrete resin layers optimizing the structural, ballistic, and FST performance of the integral armor system.

A methodology was developed to evaluate lightweight armor for ballistic- and damage-tolerance performance. Metrics for efficiency were defined for superior damage-tolerant armors that uniformly distribute damage through the thickness, while minimizing the extent of in-plane damage. Hybrid composite integral armors offering this balance of energy dissipation offer potential for improving V_{50} for a given areal density or significantly improving damage tolerance measured through improved residual strength after ballistic impact.

The VARTM-manufactured panels demonstrated equivalent ballistic performance to that of the prepreg material system at reduced cost. The through-thickness stitching reduced the extent

of damage to the composite targets in both direct impact from a projectile and when the composite is used as a backing plate for ceramic armor. In the case where damage tolerance drives the design of the structure, the use of through-thickness stitching may permit the designer to reduce the areal density of the laminate while maintaining the same effective damage size for the composite.

Future work will focus on the stitching density to optimized apparent toughness of the system, while limiting the reduction of in-plane properties.

5. References

1. Pike, T., M. McArthur, and D. Schade. "Vacuum Assisted Resin Transfer Molding of a Layers' Structural Laminate for Application on Ground Combat Vehicles." *Proceedings of the 28th International SAMPE Technical Conference,* pp. 374–380, Seattle, WA, 4–7 November 1996.

2. Fink, B. K. "Performance Metrics for Composite Integral Armor." *Proceedings of Fourteenth Annual Technical Conference of the American Society for Composites,* Dayton, OH, September 1999.

3. Fink, B. K., J. W. Gillespie, Jr., K. R. Bernetich, and E. F. Gillio. "One-Step Resin Transfer Molding of Multifunctional Resin Composites Consisting of Multiple Resins." U.S. Patent Application No. 08/956,595, October 1997.

4. Fink, B. K., S. H. McKnight, and J. W. Gillespie Jr. "Co-injection Resin Transfer Molding for Optimization of Integral Armor." *Proceedings of the Army Science Conference,* Norfolk, VA, 15–17 June 1998.

5. Gillio, E. F. "Co-injection Resin Transfer Molding of Hybrid Composites." Masters Thesis, Department of Mechanical Engineering, University of Delaware, 1997.

6. Gillio, E. F., J. W. Gillespie, Jr., R. F. Eduljee, K. R. Bernetich, S. G. Advani, and B. K. Fink. "Manufacturing of Composites With the Co-Injection Process." American Institute of Aeronautics and Astronautics 38th Structures, Structural Dynamics and Materials Conference, American Institute of Aeronautics and Astronautics, 7–10 April 1997.

7. Immordino, K. M. "Characterization of the Polysulfone/Epoxy Interphase for Bonding Thermoplastic Composites." Masters Thesis, Materials Science Program, University of Delaware, 1996 (also published as Center for Composite Materials Technical Report No. 96–29).

8. Don, R. C., S. H. McKnight, and J. W. Gillespie, Jr. "A Study of Improved Bonding Techniques for High Performance Thermoplastic Composites." *Proceedings of the 10th Annual ASM/ESD Advanced Composites Conference,* Dearborn, MI, 7–10 November 1994.

9. Monnard, V., P. E. Bourban, J. A. Manson, D. A. Eckel II, J. W. Gillespie, Jr., S. H. McKnight, and B. K. Fink. "Processing and Characterization of Welded Bonds Between Thermosets and Thermoplastic Composites." *18th International SAMPE European Conference,* Parts, La Defense, France, 23–25 April 1997.

10. Bernetich, K., B. K. Fink, and J. W. Gillespie, Jr. "Co-Injection Resin Transfer Molding of Vinyl Ester and Phenolic Composites." *43rd International SAMPE Symposium and Exposition*, Anaheim, CA, 31 May–4 June, 1998.

11. Newton, C.H., B. K. Fink, S. H. McKnight, G. R. Palmese, and J. W. Gillespie, Jr. "Non-Polluting Composites Repair and Remanufacturing for Military Applications: An Environmental and Cost-Savings Analysis." *Special Interim Report to the Strategic Environmental Research and Development Program Office*, September 1998.

12. Hartmann, B., and S. Jones. "Activity Based Cost Analysis for Manufacturing of the Composite Armored Vehicle." *ARL/Tuskegee University Annual Program Review,* November 1997.

13. Chou, S. C., and E. DeLuca. "Dynamic Response of S-2 Glass Reinforced Plastic Structural Armor, A Progress Report." ARL-SR-5, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, December 1993.

14. Bless S. J., et al. "Ballistic Penetration of S-2 Glass Laminates." Third TACOM Army Coordination Conference for Light Combat Vehicles, vol. II, 17–19 Febuary 1987.

15. Bless S. J., et al. "Ballistic Penetration Study of S-2 Glass/Phenolic Spall Liner Materials." *Combat Survivability Symposium,* vol. II, U.S. Army Tank-automotive and Armaments Command, Warren, MI, 15–17 April 1991.

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13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Research Laboratory (ARL) and the University of Delaware (UD) have developed an enabling technology to produce a polymer matrix composite-based integral armor with improved multihit ballistic capability. Current applications for integral armor composites include the Composite Armored Vehicle (CAV) technology demonstrator and Crusader self-propelled howitzer platforms. Present integral armor manufacturing processes involve adhesive bonding of a composite structure with ballistic armor tiles, spall shield, and nuisance cover. ARL, UD, and the CAV/Crusader composite structure contractor, United Defense Limited Partnership (UDLP), assessed through-thickness stitching to improve the multihit capability and reduce manufacturing costs. The patent-pending co-injection resin-transfer molding (CIRTM) process was used to produce a stitched, co-injected integral armor panel that demonstrated improved multihit capability. The spall shield was fabricated with a phenolic resin for fire, smoke, and toxicity protection, while the remainder of the integral armor (structural composite resin encapsulating the tiles and the nuisance cover) was fabricated with an epoxy resin for structural performance. Through-thickness stitching and CIRTM were used to enhance the damage tolerance and to reduce the cost of the armor.

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composite material, damage tolerance, ballistic testing, integral armor, co-injection resin transfer molding

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